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The formation of a comfortable outdoor thermal environment in a Southeast Asian sustainable city

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Abstract

This study discusses the present and future urban thermal environment in Metro Manila which is a city in the Tropical zones. The purpose is to establish an evaluation method of urban thermal environment from viewpoints of land use and land cover by case study for Metro Manila. We focused on an urban block as a unit for evaluating urban thermal environment and its explanatory variables for classifying urban blocks were decided. In the results, the whole urban blocks of Metro Manila were classified as several groups. The results were also verified using HIP (Heat Island potential) proposed by the authors.

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Keywords: Sustainable city; thermal environment; heat island; Metro Manila

1. Introduction

In recent years, many cities in the world have placed a high value on the safety of buildings or the prevention of the deterioration of the external environment. If those factors are pursued excessively, though, it will result in tight designs for individual buildings. Thus, if those tight buildings are constructed in tropical regions such as Metro Manila, the use of air-conditioning will be essential for achieving a comfortable indoor environment. Once this

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concept spreads to the entire Metro Manila area, it may lead to a significant rise in the load to the external environment.

The urban heat island phenomenon in major cities shows that the change of land use and land cover has imposed a great deal of load on the environment. The concept of a sustainable city, that puts less load on the environment is gradually gaining consensus in a number of cities worldwide. Therefore, to reexamine the significance of a city from the standpoint of urban and architectural planning is an important step in realizing a sustainable city.

In this study, we will evaluate thermal comfort of outdoor living spaces in the existing urban housing block model and proposed housing block model. Next,we will examine the feasibility of the sustainable city, where the basic concept of controlling the urban heat island effect is applied to the entire metropolitan area.

2. Townscape planning considering the climate

In the planning of comfortable urban life, it is important to consider characteristics of the regional climate. Figure 1shows a climograph of the world's major cities, which is created in order to grasp the climate characteristics. Figure 2 shows Metro Manila's yearly changes in temperature, relative humidity, solar radiation and precipitation. The tropical monsoon climate of Metro Manila is typically characterized by high temperature and high humidity throughout the year. Thus, it takes some effort to achieve a cool environment. The solar altitude is high all year and the maximum accumulated value of daily solar radiation can go as high as 6,000 W/m2 in the dry season. Even during the rainy season the daily accumulated value shows approximately 4,000 W/m2. In this area, it is ideal to prevent solar radiation by creating outdoor shading spaces. And it is desirable to control solar insulation entering a building as much as possible.

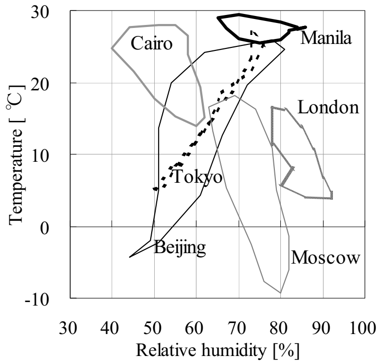


Fig. 1. Climograph of the World's Major Cities

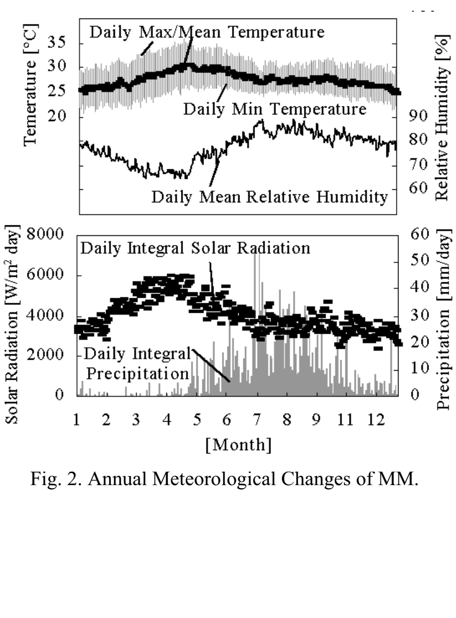


Fig. 2. Annual Meteorological Changes of MM.

Metro Manila also has abundant precipitation. Figure 3 shows the number of precipitation days for each month and precipitation hours for each month assembled using the data in Figure 2. During the rainy season from June to November, it rains once every other day or more frequently. In the hottest months of April and May, it rains five to ten days a month. By allowing an abundant amount of precipitation in the ground and by utilizing the latent heat from evaporation, the ground surface temperature goes down and it will be, or can be, cooler. We recognize the importance of the fact that though the amount of evaporation is reduced in the shade the effect of latent heat evaporation lasts relatively longer than that of in the sun, which is conventionally focused on. Considering the latent heat of vaporization and its effect on the ground surface in the shade, the daily vaporization is believed to be approximately 5 mm. Thus, if there was a 5-mm rainfall or more, we could count on the cooling effect caused by the latent heat throughout the day.

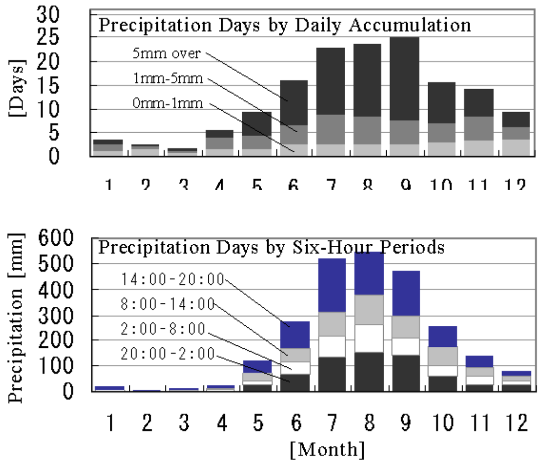


Fig. 3. Annual Precipitation Characteristics of MM

Also, the tropical monsoon climate has high potential for the growth of greenery. In trees with a large tree crown, the surface temperature of the crown does not go higher than the air temperature. Those trees provide shading on the ground surface and buildings. In the shade formed by a large tree crown, the ground surface temperature is lower than the daytime air temperature. The tree-crown surface temperature is equivalent to the air temperature. Even on the paved surface, the daytime surface temperature in the shade is equivalent to the air temperature. When the precipitation is absorbed in the ground and the shaded surface is slightly damp, the daytime surface temperature will be lower than the air temperature. If there is wind, the space will be further cooled.

To utilize the latent heat of vaporization to cool a town, it is important to secure green space and bare land. However, urbanization has rapidly deprived Metro Manila of green space and bare land. As will be described in the next chapter, the combined percentage of green space and bare land is less than 10%. Therefore, the reality is that we cannot count on the cooling effect by the latent vaporization heat.

From the all the above current characteristics of Metro Manila and its climate, the design disciplines required to realize comfortable townscape can be compiled as follows.

1. Create as Much Outdoor Shading as Possible.
   a. Create shading spaces that include trees with a large tree crown.
   b. Create as many shading spaces as possible by paying careful attention in designing the shape and arrangement of buildings.
2. Prevent Solar Radiation on Buildings
   a. Planting rows of evergreens and wall planting will be carried out along the wall on the east-west side.
   b. Rooftop planting will be actively carried out.
   c. Incorporate greenery into the veranda and use it as an outdoor living space.

3. Aggressively Utilize the Cooling Effect by the Latent Heat of Vaporization.
   a. Secure water-contained surfaces such as bare land and the permeable paved surface.
   b. Control the evaporation lasting longer and lower the surface temperature by creating shading on water-containing surfaces.
4. Secure the Cross-Ventilation.
   a. Make a wind path that can bring air to living spaces.

3. Proposal of the Southeast Asian type townscape

We examined the townscape planning with consideration to its climate in the above chapter. The existing Metro Manila landscapes can be divided into some categories from the standpoint of land use or land cover. If open space and green space are excluded, 90% or more of land use are commercial or residential. Most typical ones are high-rise commercial districts such as the Makati business district and areas for high-income residents and squatting by illegal habitants. For land cover, there is little greenery; the buildings and pavement surfaces are exposed to solar radiation in the daytime in the central commercial district and the squatter district. Thus, solar radiation can easily be stored. Furthermore, due to the artificial land cover, when it rains the rainwater is not absorbed in the ground, creating runoff.

In light of those conditions and in view of Metro Manila's climatic characteristics, the proposal aims at a commercial district and residential area. In this paper, we take up examples of the residential district and introduce design conditions and concepts.

Population density is an important problem when considering habitation in Southeast Asia. The annual rate of Metro Manila population increase from the 1980s to the 1990s was approximately 3%. This figure is significantly large compared to the world's other megalopolises. The population was approximately 9.5 million as of 1995. By 2015, it is expected to reach 13.5 million. Converting this figure to population density, it will be 210 persons /ha, thus, making it essential to have a high-density housing model. In this paper we will establish the floor area rate for the proposed district based on the existing data on gross-net population density and estimated data on future population influxes. Considering the relationship between the gross-net population density and the building coverage or floor area rate, we establish the floor space for the low-income housing to be 10m2/person, the middle-income housing 20 m2/person and the high-income housing 60 m2/person.

Figure 4 shows a menu example of the climate-conscious environmental symbiosis method that is applicable for buildings. When proposing this method, we use this menu and adopt design disciplines in the above chapter as a specific environmental symbiosis method at the on-site level.

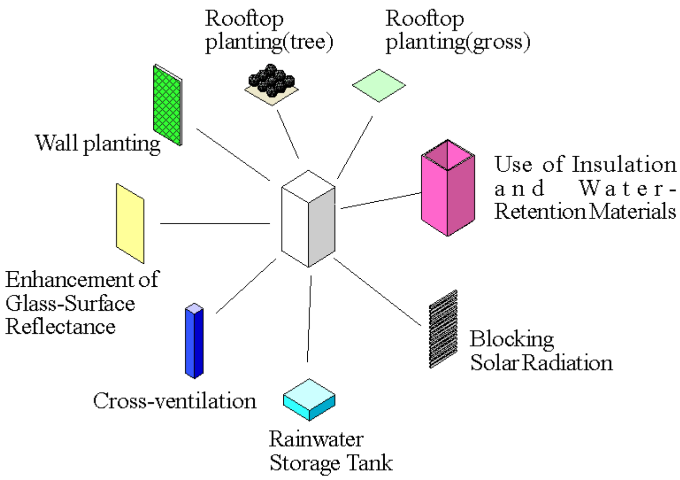


Fig. 4. Components of the Green Architectural Method Applicable for Buildings

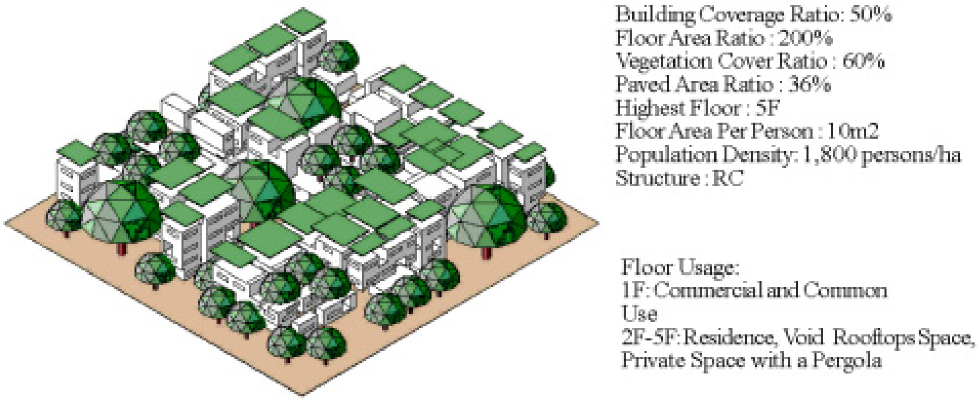


Fig. 5. A Model of the Southeast Asian low-rise high-density residential block

Figure 5 shows one model example of the low-income housing block by the environmental symbiosis method. Currently, as residents from rural regions move into the city and form slums as squatters, their numbers are estimated to grow in the future. With that in consideration, this model can accommodate illegal habitants and make improvement in the urban thermal environment and housing environment. This high-density housing model is an example of a low-rise model. Acacia trees with a generally large tree crown are used. Uneven building structures and "void" spaces are designed to create more shading during the daytime. In shading spaces, cross ventilation is secured for cooler and more comfortable living with a sense of openness. The ground floor mostly consists of pilotis. Thus, the facility can easily turn into a public commercial space. Planted on the premises are 20m or higher acacia trees. Large spaces under the tree crown can be utilized as community space. On the rooftop are pergola and trees for blocking as much solar radiation as possible. It can be used as citizens' community space such as markets.

4. Thermal environmental evaluation.

Here, we will evaluate thermal comfort of outdoor living spaces in the existing urban housing block model and proposed housing block model.

The main regulating factors for thermal comfort are the air temperature, humidity, air velocity, and radiation. Compared to other factors, Metro Manila's radiation environment can greatly vary depending on the spatial composition of the district. Therefore, we used the 1.5m-high MRT (mean radiant temperature, ^{o}C) distribution from the ground in intervals in a living space as an index to evaluate the comfort in the district. MRT is calculated by the total of the product of the form coefficient of each side from a human body and surface temperature of each field. Since MRT is suitable for evaluating urban comfort attributed to the arrangement of buildings, roads, and the structure and materials of exterior building walls, it is also a particularly effective index for evaluation of coolness in sustainable urban blocks with planting.

To calculate the MRT distribution in a block, first, the total surface temperature distribution must be obtained. Figure 6 shows the simulation process through which three-dimensional CAD data are input and the total surface temperature distribution is obtained. This is part of the simulation method (Iino, 1996) developed for the purpose of evaluating the urban thermal environment. By this method one can evaluate living-space comfort by calculating the total surface temperature distribution that includes surrounding ground and building wall surfaces, thereby obtaining the MRT distribution. At the same time, by obtaining the HIP (heat island potential, ^{o}C), one can also evaluate its influence on the urban heat island phenomenon. Details about HIP will be discussed in the next chapter.

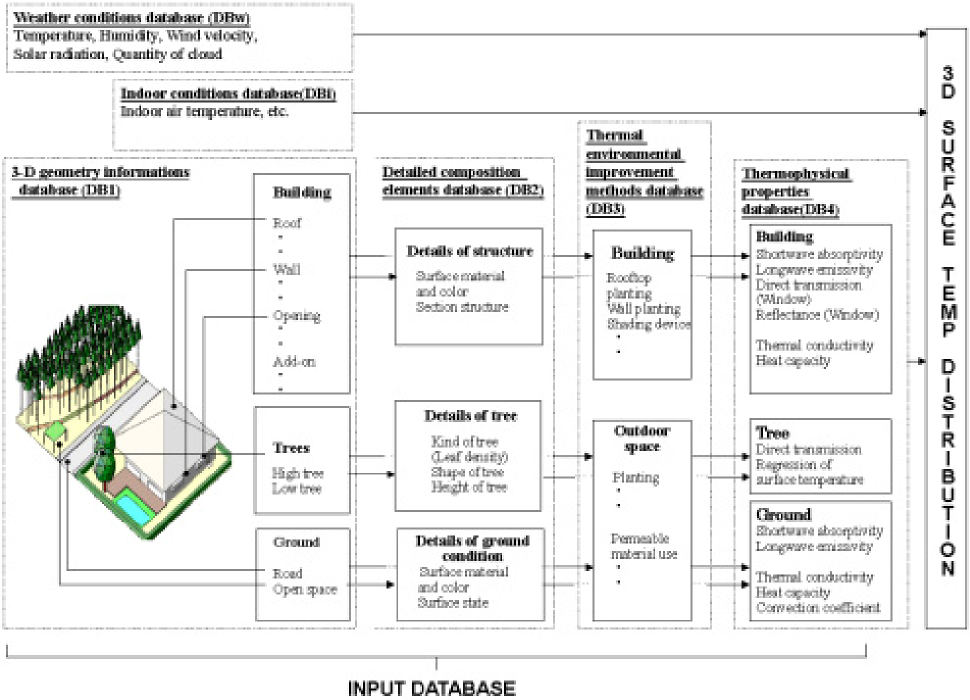


Fig. 6. Calculation Method of Urban Block Surface Temperature

Figure 7 shows the surface temperature calculation results in the proposed sustainable housing block model and the same urban block model with trees removed. The subject months were April and May on typical clear days when a deterioration of the thermal environment is most expected. From surface temperature calculation results, we were able to obtain information on the difference in the wall surface temperature depending on the building direction at the pedestrian's eye level, information comparing between trees and lawns and buildings or paved surfaces with a large thermal capacity as well as different ground surface materials and their relationship to the surface temperature.

In the urban block model without trees, the daytime temperature on the sun-baked paved surface rose as high as 53^{o}C. Since the solar radiation heat is absorbed and stored in buildings and on paved surfaces, high temperatures are maintained even outside in the evening. However, in the sustainable housing block model with trees, the temperature was equivalent to the air temperature even in the afternoon because of shading from large tree crowns and the unevenness of building surfaces. With this low surface-temperature distribution, we were able to observe a control effect on the urban heat island phenomenon in the whole urban area. This will be discussed in detail in the next chapter.

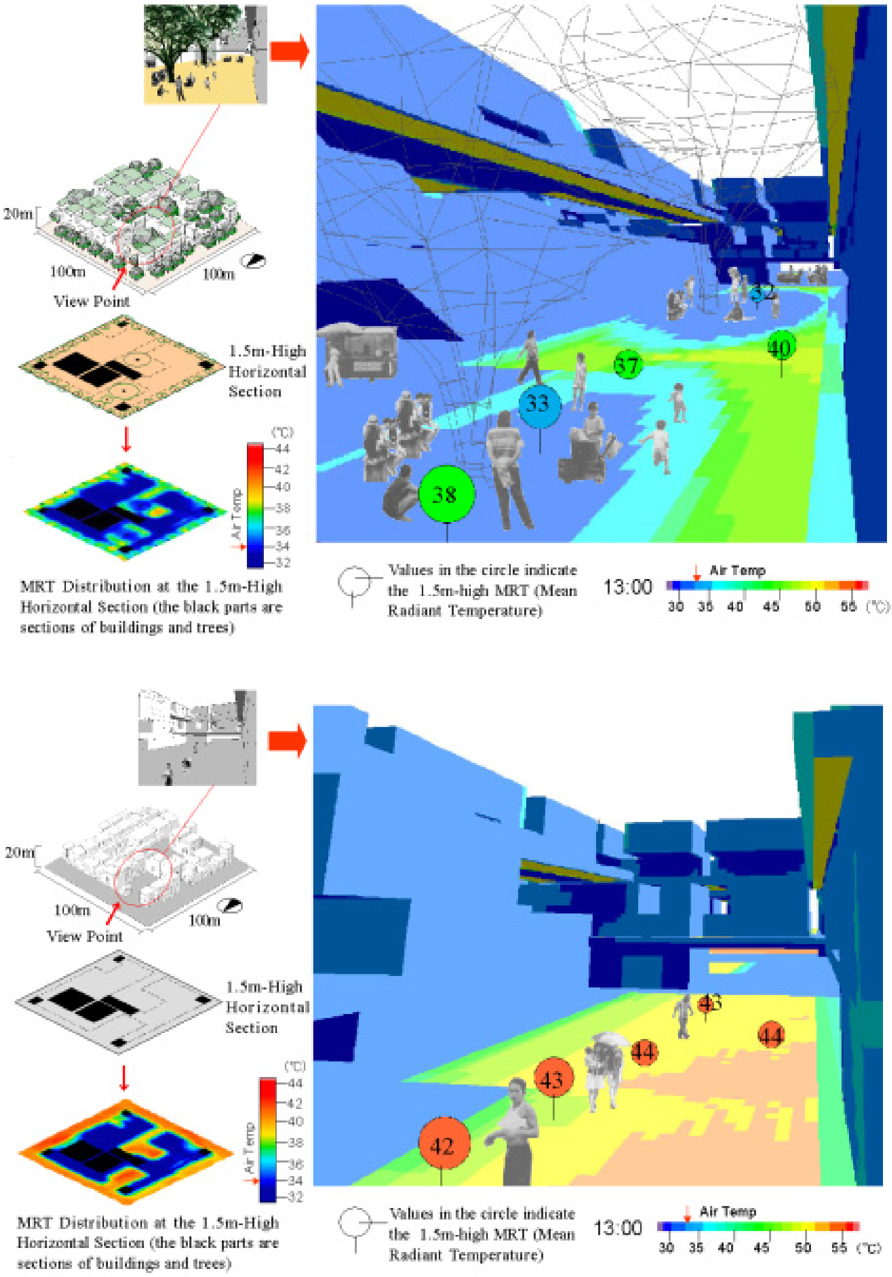


Fig. 7. The Surface Temperature Calculation Result of Sustainable Housing Block and the Same Block Model with Trees Removed

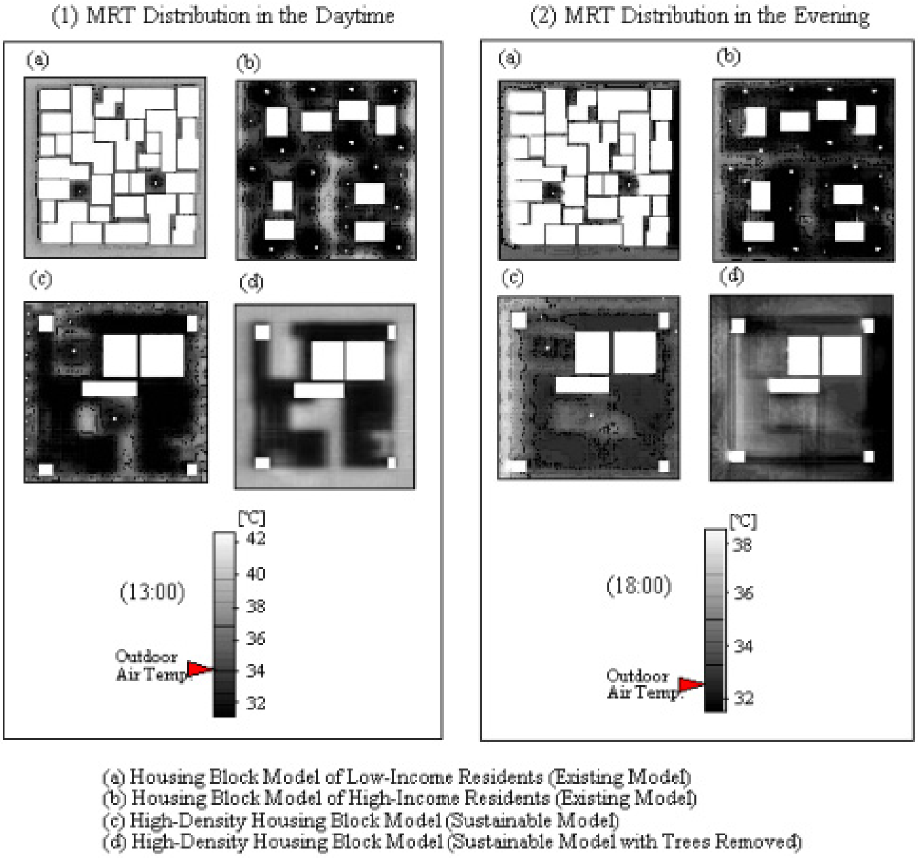


Fig. 8. 1.5m-High MRT Distribution From the Ground in the Existing Housing Block Model and Sustainable Housing Block

Figure 8 shows the 1.5m-high MRT distribution from the ground in intervals, which were obtained from the surface temperature distribution in the existing urban housing block model, the proposed sustainable housing block model and the sustainable housing block model without trees. The overall MRT distribution at noon with a high solar altitude in the existing low-income model was approximately 42^{o}C, 10^{o}C higher than the air temperature. In contrast, in the sustainable block model, the MRT distribution was 30^{o}C to 32^{o}C, lower than the air temperature. Furthermore, while the MRT distribution was higher than the air temperature in the evening in the existing model, in the sustainable block model, it was slightly lower because of the reflectance of daytime solar radiation and evapotranspiration from the presence of greenery. In the proposed sustainable model with trees, trees and uneven building sections helped create continuous cool spots during the daytime. Thus, outdoor spaces can be actively used as comfortable living spaces.

5. Alterations in land use and the urban heat island phenomenon

The urban heat island phenomenon occurs mainly from complex combinations of an artificial change in land cover, an increase in anthropogenic heat, and the generation of contaminants. In this chapter we will focus on "artificial alterations in land cover" that are closely associated with architectural and urban planning.

In the process of artificial land cover in urban areas affecting the urban thermal environment, the following four contributing factors were pointed out.

1. Increase in Solar Absorptance on the Urban Surface
   Multiple reflections occur when the ground surface is uneven due to a concentration of buildings. Thus, it appears that the solar absorptance value of the ground surface is much higher than that of individual urban-structural materials such as concrete and asphalt.
2. Increase in Heat Capacity
   When the ground surface is covered with materials with high heat capacity such as a paved surface and reinforced concrete buildings, it results in thermal storage of solar energy. The ground surface also retains the high temperature during the nighttime.
3. Decrease in Cooling Effect due to Evapotranspiration
   Because of the significant decrease in soil and greenery areas, the cooling effect by evapotranspiration on the urban ground surface can no longer be expected.
4. Decrease in Diffusion Effect of Heat and Contaminants
   Figure 9 illustrates the thermal image of the Metro Manila urban area on a clear day during the dry season. Due to the lack of greenery area, the temperature of sun-baked buildings or pavement surfaces can be more than 20^{o}C higher than the air temperature. It is easily imaginable that pedestrians would feel discomfort from the reflected solar radiation and the surrounding long-wave radiation. The vicious cycle is that since the outside air also rises, it can increase the cooling load of individual buildings in the area. In other words, the fundamental solution of the urban heat island effect lies in the comprehensive review of urban land use and land cover.

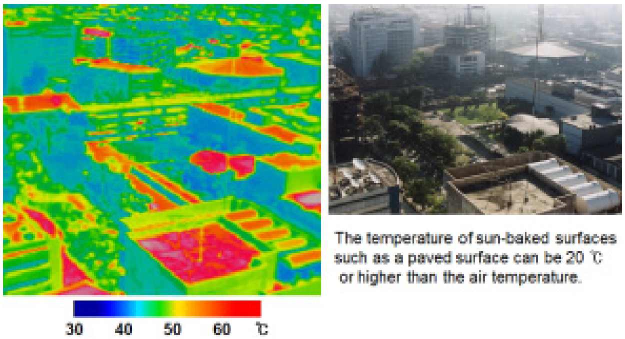


Fig. 9. Example of urban thermal images at noon in the dry season.

6. Analysis method of the relationship between land cover and urban heat islands

Here, we will outline our method of analyzing the relationship between land cover and urban heat islands.

6.1. Urban blocks as the minimum urban developmental unit

Past studies on land cover and the urban heat island effect have discussed only the influence caused by urban land use and land cover and the "mesh" arrangement after dividing the city into "mesh" blocks of several hundred meters to several kilometers. However, to examine the ultimate impact from the arrangement of buildings, the ground surface and trees on the urban environment, it is necessary to establish the developmental unit so that the explanation variables that represent land use and land cover can also be established.

"An urban block," which is an urban area surrounded by arterial roads, railroads and rivers, is considered to be the minimum plan unit, and it corresponds to the municipal unit of "Barangay" in Metro Manila. Thus various elements of architectural scale can be parameterized and those can also be treated as attributes in individual urban blocks. In other words, we can continuously evaluate an urban thermal environment from an architectural scale (thermal comforts in outdoor spaces) to an urban scale (extensive urban heat island effect).

6.2. Index to evaluate the urban thermal environment.

The direct evaluation index of urban heat islands is the heat island intensity, that is to say, the difference in temperature between the urban center and suburbs. However, when discussing the ideal urban land use and land cover from the standpoint of the urban thermal environment, the impact to the surrounding environment resulting from the land use and land cover in urban blocks should be used as the index. We have given special attention to the following two indices:

1. Entire urban scale: "Heat Island Potential (HIP)," for evaluating thermal environment in an urban block and its surrounding blocks.
2. Urban block scale: "Mean Radiant Temperature (MRT)," for evaluating the thermal amenity in an outdoor space of a block.
3. The efficacy of MRT is explained in the above chapter.
4. HIP was developed as an index showing the potential to cause the urban heat island effect on land cover. The characteristics in the difference between surface temperature and air temperature in individual urban blocks can be provided by the following Equation (1):

$$\mathrm{HIP} = \frac{\int_{\mathrm{all\_urban\_surface}} (\mathrm{T_s} - \mathrm{T_a})\,\mathrm{dS}}{\mathrm{A}} \qquad (1)$$

where, Ts is the surface temperature (°C) on the micro surface, Ta the mean temperature (°C), A the horizontal projection area (m2) and dS the micro surface area (m2), respectively.

6.3. Evaluation flow of the urban thermal environment focused on land use and land cover.

The flow consists of the following four steps. [STEP 1] Constructing a Land Cover Map

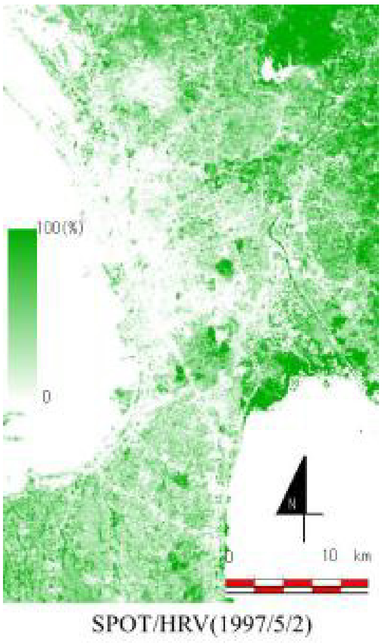


Fig. 10. Vegetation cover map of MM.

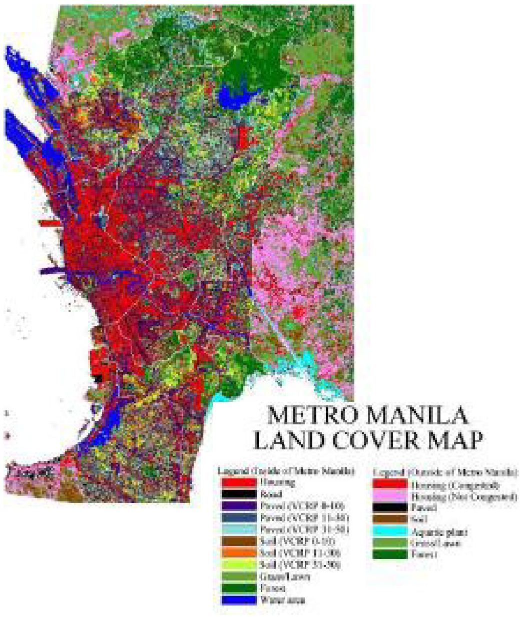


Fig. 11. Land cover map of MM

To obtain important parameters for land cover of each urban block in Metro Manila such as built-up area ratio (BAR), paved area ratio (PAR) and vegetation cover ratio (VCR), we constructed land cover maps based on map data (land use and building shapes by NAMRIA), field surveys and remote sensing data. Figure 10 shows the vegetation cover map of the entire Metro Manila area. From LANDSAT/TM images, we calculated the vegetation cover ratio for every 30m*30m pixel of the urban area (Iino, 2002). It is well known that there is extremely little greenery in low-income residential quarters and commercial districts in EDSA. At the area outside of EDSA, vegetation cover ratios in residential areas and near shopping malls are also low. Figure 11 shows the result of a land cover classification of the entire Metro Manila area with the combination of GIS data. In EDSA, both the built-up area ratio and paved area ratio, that is to say the impervious surface ratio, was high.

[STEP 2] Cluster Analysis on Urban Blocks with Land Cover Elements as Explanation Variables: Breaking down urban blocks into various types is an important step in mitigating the calculation load for the numerical simulation of heat balance as well as in identifying the target block for improvement. If we can present detailed building scale data on spaces under similar land use conditions and with similar land cover elements as attributes of urban blocks and if we can break them down into patterns, it will be possible to discuss the heat balance of the whole urban area by simulating the representative block from each cluster. After performing the cluster analysis in Figure 12, we were able to break down approximately 22,000 Metro Manila urban blocks to approximately 1,500 urban blocks (Iino, 2002).

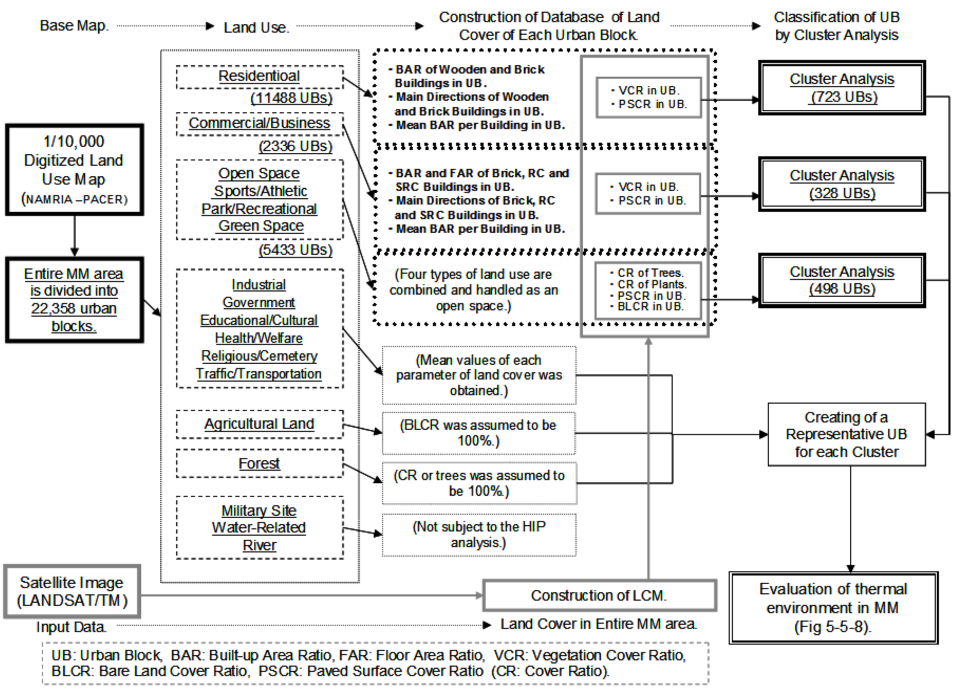


Fig. 12. Process of cluster analysis of UB in entire MM area.

[STEP 3] Selecting the Representative Urban Block and Calculating the Total Surface Temperature: In this step, we selected one representative block from cluster blocks and conducted a numerical simulation of heat balance. We had already developed the algorithm of numerical simulation of heat balance of all surfaces of an urban block (Iino, 1996). Figure 13 shows examples of calculation results of surface temperature distribution of Metro Manila's residential and commercial/business blocks(Iino, 2002). The characteristics of surface temperature distributions of those urban blocks were determined by the difference in heat capacity due to the building structure, the existence of areas shaded by trees, and the condition of the ground surface.

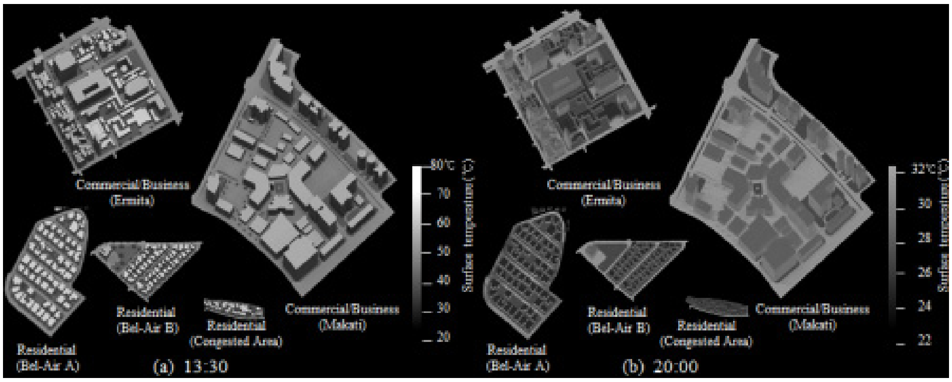


Fig. 13. Samples of calculation results of surface temperature distribution of urban blocks.

[STEP 4] Calculating the Urban Block HIP and MRT Distribution: In this step, we calculated the HIP and MRT of the representative block and made HIP maps for the entire urban area. Figure 14 shows the diurnal HIP change of all 1,500 representative blocks in Metro Manila. The daily HIP change was 14-28 ^{o}C in the residential section and 20-26 ^{o}C in the commercial section. The decrease in vegetation cover and the increase in the floor area ratio both contributed to the HIP increase during the daytime and at sunset.

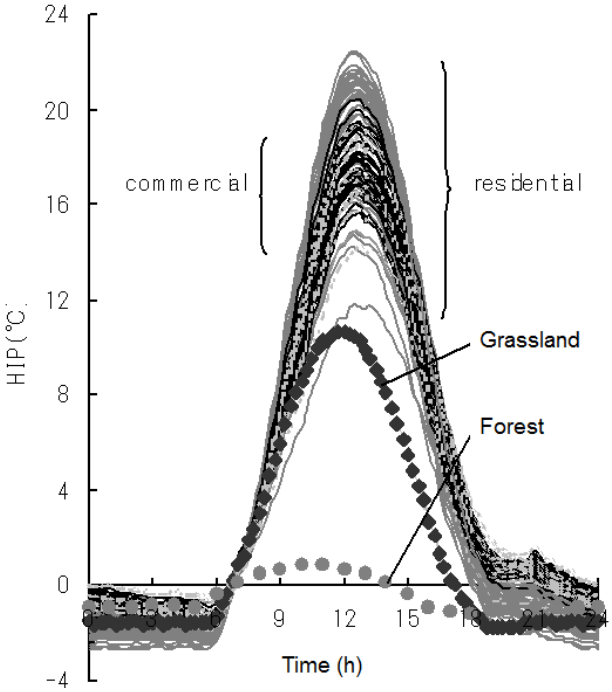


Fig. 14. Diurnal change of HIP in each urban block in MM.

7. Existing condition of the urban heat island effecting metro manila and future predictions

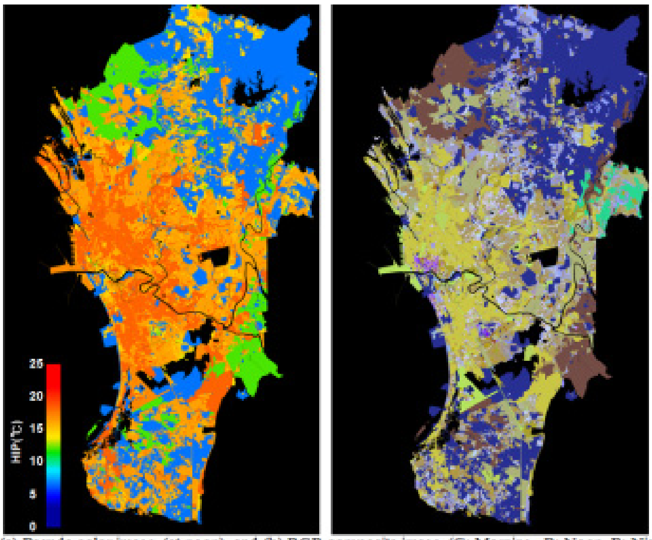
Let us introduce the case in which we attempted to express the daily HIP change by allocating and composing the afternoon HIP map and morning, afternoon and night HIPs into RGB (red-green-blue) primary colors of light (Figure 15).

In figure (a) we can find that areas with significantly high HIP values at noon were widely spread on the inside of EDSA in Manila and Makati. There is also a HIP peak in suburbs such as Kalookan.

In the map (b), urban blocks of which HIP is high all day, it is shown in white. This color is commonly observed in urban blocks such as Manila or Malabon where illegal habitants are concentrated. The decline in greenery and permeable surfaces has resulted in the significant increase HIP in the afternoon. Thus, this is a major contributing factor to the urban heat island phenomenon.

Table1 shows the control measures against the urban heat island effect. Considering Metro Manila's climate, tree planting is one of the most effective control methods. Equally important is to ensure such water-containing surfaces as the soil in bare land and impervious pavement as much as possible to actively utilize abundant rainwater.

We proposed several urban block models based on this concept in the above chapter. Figure 16 illustrates the future HIP map when the effective use of greenery and permeable pavement is aggressively adopted in Metro Manila urban blocks. According to the map, sustainable urban blocks will have helped to control the urban heat island effect. In other words, by implementing the effective and active use of greenery and permeable pavement, there is an ample possibility to realize a sustainable city.

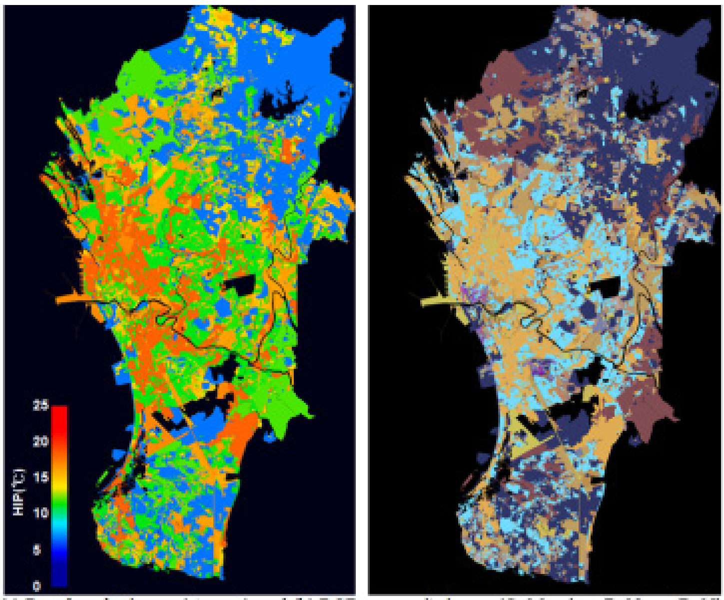


(a) Pseudo color image (at noon), and (b) RGB composite image (G: Morning, R: Noon, B: Night).

Fig. 15. HIP map of present MM.

Table 1. Menu of Urban Heat Island Counter measures.

A		A Improvement in Ground Surface Cover
	a.	Improvements in Paving Materials
		Improvements in Reflectance and Water Retention
	b.	Improvements in Building Materials
		Use of lighter shades, better windowpane reflectance
	c.	Tree Planting
		Green space in the park, forest conservation, river conservation, planting around buildings and roads, planting in gardens
	d.	Water
		Open channels in the river, creating water areas
B		B Reduction of Antropogenic Heat
	a.	Energy-Saving Facilities
		Higher efficiency and optimum use of energy-consuming appliances and air-conditioning, proper operation of the air-conditioning system
	b.	Heat Load Reduction with Better Buildings
		Thermal insulation, tree planting on the premises, building materials of better water retention capacity, wall materials of better reflectance
	c.	Use of Natural Energy
		Use of solar energy, solar power generation, hybrid energy sources
	d.	Use of Unutilized Energy
		Use of unutilized water or urban exhaust heat, energy recovery from waste
	e.	District Measures
		District heating and cooling, reduction in automobile traffic, adoption of low-emission cars
C		Improvement in Urban Form
	a.	Positive Use of Wind and Water Paths
		Improvement in building arrangement, utilization of regional climatic characteristics
	b.	Realization of Sustainable City
		Cascade efficiency of energy source
	c.	Recycling-Conscious City
		Efficient use of energy, use of recyclable matters



(a) Pseudo color image (at noon), and (b) RGB composite image (G: Morning, R: Noon, B: Night)..

Fig. 16. HIP map in MM after sustainable urban development.

8. Conclusions

This study discussed the present and future urban thermal environment in Metro Manila which is a city in the tropical zones. The purpose was to establish an evaluation method of urban thermal environment from viewpoints of land use and land cover by case study for Metro Manila. We focused on an urban block as a unit for evaluating urban thermal environment and its explanatory variables for classifying urban blocks were decided. In the results, the whole urban blocks of Metro Manila were classified as several groups. The results were also verified using HIP (Heat Island potential) proposed by the authors.

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